Introduction to Operating Systems

What's an OS?

The OS is a layer between applications and hardware to ease development.

- **Abstraction**. provides abstraction for applications:
  - manages + hides hardware details
  - uses low-level interfaces (not available to applications)
  - multiplexes hardware to multiple programs (*virtualization*)
  - makes hardware use efficient for applications
- **Protection**.
  - from processes using up all resources (*accounting*, *allocation*)
  - from processes writing into other processes memory
- **Resource Management**.
  - manages + multiplexes hardware resources
  - decides between conflicting requests for resource use
  - *goal*: efficient + fair resource use
- **Control**.
  - controls program execution
  - prevents errors and improper computer use

⇝ **no universally accepted definition**

Hardware Overview

- **Bus**: CPU(s)/devices/memory (conceptually) connected to common bus
  - CPU(s)/devices competing for memory cycles/bus
  - all entities run concurrently
  - *today*: multiple buses
- **Device controller**: has local buffer and is in charge of particular device
- **Interplay**:
  1. CPU issues commands, moves data to devices
  2. Device controller informs APIC that it has finished operation
  3. APIC signals CPU
  4. CPU receives device/interrupt number from APIC, executes handler

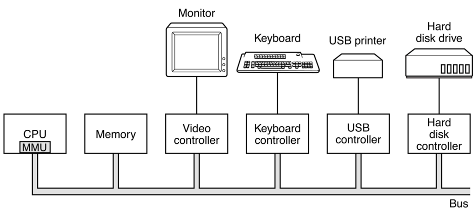


Figure 1: Traditional bus design.

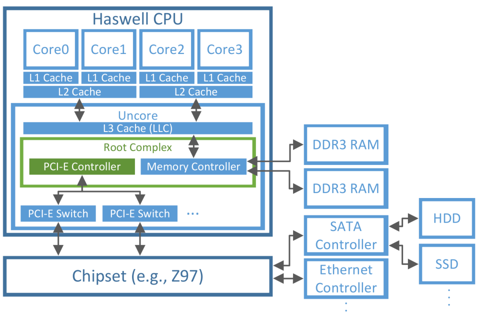


Figure 2: Modern bus design.

Central Processing Unit (CPU) — Operation

- **Principle**:
  1. *fetches* instructions from memory,
  2. *executes* them
- **During execution**: (meta-)data is stored in CPU-internal registers, i.e.
  - general purpose registers
  - floating point registers
  - instruction pointer (IP)
  - stack pointer (SP)
  - program status word (PSW)

CPU — Modes of Execution

- **User mode** (x86: *Ring 3/CPL 3*):
  - only non-privileged instructions may be executed
  - cannot manage hardware → *protection*
- **Kernel mode** (x86: *Ring 0/CPL 0*):
  - all instructions allowed
  - can manage hardware with *privileged instructions*

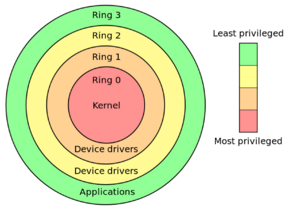


Figure 3: The different protection layers in the *ring model*.

Random Access Memory (RAM)

- **Principle**: keeps currently executed instructions + data
- **Connectivity**:
  - *today*: CPUs have built-in **memory controller**
  - *CPU caches*: "wired" to CPU
  - *RAM*: connected via pins
  - *PCI-E switches*: connected via pins

Caches

- **Problem**: RAM delivers instructions/data slower than CPU can execute
- **Locality principle**:
  - *spatial locality*: future refs often near previous accesses (e.g. next byte in array)
  - *temporal locality*: future refs often at previously accessed ref (e.g. loop counter)
- **Solution**: *caching* helps mitigating this memory wall
  1. *copy* used information temporarily from slower to faster storage
  2. *check* faster storage first before going down *memory hierarchy*
  3. if *not found*, data is copied to cache and used from there
- **Access latency**:
  - *register*: ~1 CPU cycle
  - *L1 cache* (per core): ~4 CPU cycles
  - *L2 cache* (per core pair): ~12 CPU cycles
  - *L3 cache/LLC* (per uncore): ~28 CPU cycles (~25 GiB/s)
  - *DDR3-12800U RAM*: ~28 CPU cycles + ~ 50ns (~12 GiB/s)

Device controlling

- **Device controller**: controls device, accepts commands from OS via *device driver*
- **Device registers/memory**:
  - *control* device by writing device registers
  - *read* status of device by reading device registers
  - *pass data* to device by reading/writing device memory
- **Device registers/memory access**:
  1. **port-mapped IO** (PMIO): use special CPU instructions to access port-mapped registers/memory
  2. **memory-mapped IO** (MMIO):
     - use same address space for RAM and device memory
     - some addresses map to RAM, others to different devices
     - access device's memory region to access device registers/memory
  3. **Hybrid**: some devices use hybrid approaches using both

Summary

- The OS is an **abstraction** layer between applications and hardware (multiplexes hardware, hides hardware details, provides protection between processes/users)
- The CPU provides a **separation** of User and Kernel mode (which are required for an OS to provide protection between applications)
- CPU can execute commands faster than memory can deliver instructions/data — memory **hierarchy** mitigates this memory wall, needs to be carefully managed by OS to minimize slowdowns
- device drivers **control** hardware devices through PMIO/MMIO
- Devices can **signal** the CPU (and through the CPU notify the OS) through interrupts

OS Concepts

OS Invocation

- OS Kernel does **not** always run in background!
- Occasions invoking kernel, switching to kernel mode:
  1. **System calls**: User-Mode processes require higher privileges
  2. **Interrupts**: CPU-external device sends signal
  3. **Exceptions**: CPU signals unexpected condition

System Calls — Motivation

- **Problem**: protect processes from one another
- **Idea**: Restrict processes by running them in user-mode
- ⇝ **Problem**: now processes cannot manage hardware,...
  - who can switch between processes?
  - who decides if process may open certain file?
- ⇝ **Idea**: OS provides **services** to apps
  1. app calls system if service is needed (**syscall**)
  2. OS checks if app is allowed to perform action
  3. if app may perform action and hasn't exceeded quota, OS performs action in behalf of app in kernel mode

System Calls — Examples

- `fd = open(file, how,...)` – open file for read/write/both
- documented e.g. in `man 2 write`
- overview in `man 2 syscalls`

System Calls vs. APIs

- **Syscalls**: interface between apps and OS services, limited number of well-defined entry points to kernel
- **APIs**: often used by programmers to make syscalls (e.g. `printf` library call uses `write` syscall)
- common APIs: Win32, POSIX, C API

System Calls — Implementation

- **Trap Instruction**: single syscall interface (entry point) to kernel
  - switches CPU to kernel mode, enters kernel in same way for all syscalls
  - *system call dispatcher* in kernel then acts as syscall multiplexer
- **Syscall Identification**: number passed to trap instruction
  - *Syscall Table* maps syscall numbers to kernel functions
  - *Dispatcher* decides where to jump based on number and table
  - programs (e.g. `stdlib`) have syscall number compiled in!

  ⇝ never reuse old syscall numbers in future kernel versions

Interrupts

- **Devices**: use interrupts to signal predefined conditions to OS
  - *reminder*: device has "interrupt line" to CPU (e.g. device controller informs CPU that operation is finished)
- **Programmable Interrupt Controller**: manages interrupts
  - interrupts can be *masked* (queued, delivered when interrupt unmasked)
  - queue has finite length ⇝ interrupts can get lost
- **Examples**:
  1. *timer-interrupt*: periodically interrupts processes, switches to kernel ⇝ can then switch to different processes for fairness
  2. *network interface card* interrupts CPU when packet was received ⇝ can deliver packet to process and free NIC buffer
- **Interrupt process**:
  1. CPU looks up *interrupt vector* (= table pinned in memory, contains addresses of all service routines)
  2. CPU transfers control to respective *interrupt service routine* in OS that handles interrupt

  ⇝ interrupt service routine must first save interrupted process's state (instruction pointer, stack pointer, status word)

Exceptions

- **Motivation**: unusual condition → impossible for CPU to continue processing
- ⇝ **Exception** generated within CPU:
  1. CPU interrupts program, gives kernel control
  2. kernel determines reason for exception
  3. if kernel can resolve problem ⇝ does so, continues *faulting instruction*
  4. kills process if not
- **Difference to Interrupts**: interrupts can happen in any context, exceptions always occur asynchronous and in process context

OS Concepts — Physical Memory

- up to early 60s:
  - programs loaded and run directly in *physical memory*
  - program too large → partitioned manually into *overlays*
  - OS: swaps overlays between disk and memory
  - different jobs could observe/modify each other

OS Concepts — Address Spaces

- **Motivation**: bad programs/people need to be isolated
- **Idea**: give every job the illusion of having all memory to itself
  - every job has own *address space*, can't name addresses of others
  - jobs always and only use virtual addresses

Virtual Memory — Indirect Addressing

- **MMU**: every CPU has built-in *memory management unit* (MMU)
- **Principle**: translates virtual addresses to physical addresses at every load/store
  ⇝ address translation protects one program from another
- **Definitions**:
  - *Virtual address*: address in process' address space
  - *Physical address*: address of real memory

Virtual Memory — Memory Protection

- **Kernel-only Virtual Addresses**
  - kernel typically part of all address spaces
  - ensures that apps can't touch kernel memory
- **Read-only virtual addresses**: can be enforced by MMU
  - allows safe sharing of memory between apps
- **Execute Disable**: can be enforced by MMU
  - makes code injection attacks harder

Virtual Memory — Page Faults

- **Motivation**: not all addresses need to be mapped at all times
  - MMU issues *page fault* exception when accessed virtual address isn't mapped
  - OS handles page faults by loading faulting addresses and then continuing the program

  ⇝ memory can be *over-committed*: more memory than physically available can be allocated to application
- **Illegal addresses**: page faults also issued by MMU on illegal memory accesses

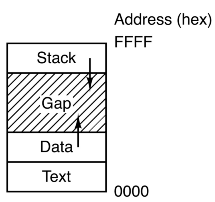
OS Concepts — Processes

- **Process**: program in execution ("instance" of program)
- each process is associated with
  - **Process Control Block** (PCB): contains information about allocated resources
  - virtual **Address Space** (AS):
    - all (virtual) memory locations a program can name
    - starts at 0 and runs up to a maximum
    - address 123 in AS1 generally ≠ address 123 in AS2
    - indirect addressing ⇝ different ASes to different programs

    ⇝ *protection between processes*

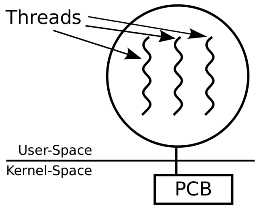
OS Concepts — Address Space Layout

- **Sections**: address spaces typically laid-out in different sections
  - memory addresses between sections *illegal*
  - illegal addresses ⇝ page fault (*segmentation fault*)
  - OS usually kills process causing segmentation fault
- **Important sections**:
  - *Stack*: function history, local variables
  - *Data*: Constants, static/global variables, strings
  - *Text*: Program code



OS Concepts — Threads

- **Thread**: represents execution state of process (≥ 1 thread per process)
  - *IP*: stores currently executed instruction (address in `text` section)
  - *SP*: stores address of stack top (> 1 threads → multiple stacks!)
  - *PSW*: contains flags about execution history (e.g. last calculation was 0 → used in following jump instruction)
  - more general purpose registers, floating point registers,...



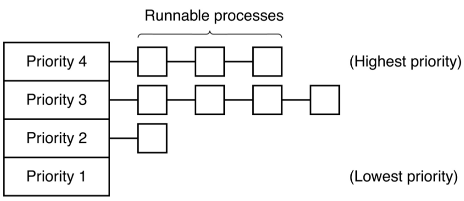
OS Concepts — Policies vs. Mechanisms

- **Mechanism**: implementation of what is done (e.g. commands to write to HDD)
- **Policy**: rules which decide when what is done and how much (e.g. how often, how many resources are used,...)

→ *mechanisms can be reused even when policy changes*

OS Concepts — Scheduling

- **Motivation**: multiple processes/threads available ⇝ OS needs to switch between them (for multitasking)
- **Scheduler**: decides which job to run next (*policy*) — tries to
  - provide fairness
  - meet performance goals
  - adhere to priorities
- **Dispatcher**: performs task-switching (*mechanism*)



OS Concepts — Files

- **Motivation**: OS hides peculiarities of file storage, programmer uses device-independent *files/directories*
- **Files**: associate *file name* and *offset* with bytes
- **Directories**: associate *directory names* with directory names or file names
- **File System**: ordered block collection
  - main task: translate (dir name + file name + offset) to block
  - programmer uses file system operations to operate on files (`open`, `read`, `seek`)
  - processes can communicate directly through special *named pipe* file (used with same operations as any other file)

OS Concepts — Directory Tree

- **Directories**: form *directory tree/file hierarchy* → structure data
- **Root Directory**: topmost directory in tree
- **Path Name**: used to specify file

OS Concepts — Mounting

- **Unix**: common to orchestrate multiple file systems in single file hierarchy
- file systems can be *mounted* on directory
- **Win**: manage multiple directory hierarchies with drive letters (e.g. `C:\Users`)

OS Concepts — Storage Management

- **OS**: provides uniform view of information storage to file systems
  - *Drivers*: hide specific hardware devices → hides device peculiarities
  - general interface abstracts physical properties to logical units → block
- **Performance**: OS increases I/O performance:
  - *Buffering*: Store data temporarily while transferred
  - *Caching*: Store data parts in faster storage
  - *Spooling*: Overlap one job's output with other job's input

Summary

- **OS**: provides abstractions for and protection between applications
- **Kernel**: does not always run — certain events invoke kernel
  - *syscall*: process asks kernel for service
  - *interrupt*: device sends signal that OS has to handle
  - *exception*: CPU encounters unusual situation
- **Processes**: encapsulate resources needed to run program in OS
  - *threads*: represent different execution states of process
  - *address space*: all memory process can name
  - *resources*: allocated resources, e.g., open files
- **Scheduler** decides which process to run next when multi-tasking
- **Virtual Memory** implements address spaces, provides protection between processes
- **File system** abstracts background store using I/O drivers, provides simple interface (files + directories)

Processes

The Process Abstraction

- **Motivation**: computers (seem to) do "several things at the same time" (quick process switching → *multiprogramming*)
- **Model**: *process abstraction* models this concurrency:
  - container contains information about program execution
  - conceptually, every progress has own "'virtual CPU"'
  - execution context is changed on process switch
  - dispatcher switches context when switching processes
  - **context switch**: dispatcher saves current registers/memory mappings, restores those of next process

Process-Cooking Analogy

- Program/Process like Recipe/Cooking
- **Recipe**: lists ingredients, gives algorithm what to do when
  ⇝ program describes memory layout/CPU instructions
- **Cooking**: activity of using the recipe
  ⇝ process is activity of executing a program
- multiple similar recipes for same dish
  ⇝ multiple programs may solve same problem
- recipe can be cooked in different kitchens at the same time
  ⇝ program can be run on different CPUs at the same time (as different processes)
- multiple people can cook one recipe
  ⇝ one process can have several worker threads

Concurrency vs. Parallelism

- OS uses currency + parallelism to implement multiprogramming
  1. **Concurrency**: multiple processes, one CPU
     ⇝ not at the same time
  2. **Parallelism**: multiple processes, multiple CPU
     ⇝ at the same time

Virtual Memory Abstraction — Address Spaces

- every process has own *virtual addresses* (`vaddr`)
- MMU relocates each load/store to *physical memory* (`pmem`)
- processes never see physical memory, can't access it directly

\+ MMU can enforce protection (mappings in kernel mode)

\+ programs can see more memory than available
  - 80:20 rule: 80% of process memory idle, 20% active
  - can keep working set in RAM, rest on disk

\- need special MMU hardware

Address Space (Process View)

- **Motivation**: code/data/state need to be organized within process
  ⇝ *address space layout*
- **Data types**:
  1. *fixed size* data items
  2. data naturally *freed in reverse allocation order*
  3. data *allocated/freed "'randomly"'*
- compiler/architecture determine how large int is and what instructions are used in text section (`code`)

- **Loader** determines based on exe file how executed program is placed in memory

Segments — Fixed-Size Data + Code

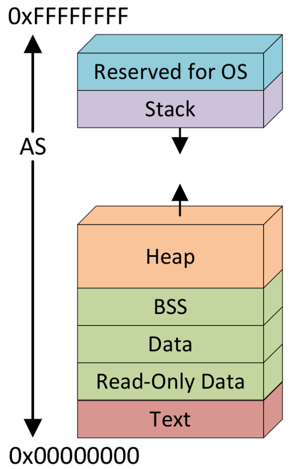
- some data in programs never changes or will be written but never grows/shrinks
  ⇝ memory can be statically allocated on process creation
- **BSS segment** (*block started by symbol*):
  - statically allocated variables/non-initialized variables
  - executable file typically contains starting address + size of BSS
  - entire segment initially 0
- **Data segment**: fixed-size, initialized data elements (e.g. global variables)
- **Read-only data segment**: constant numbers, strings
- All three sometimes summarized as one segment
- compiler and OS decide ultimately where to place which data/how many segments exist

Segments — Stack

- some data naturally freed in reverse allocation order
  - very easy memory management (stack grows upwards)
- fixed segment starting point
- store top of latest allocation in **stack pointer** (SP) (initialized to starting point)
- *allocate* `a` byte data structure: `SP += a; return(SP - a)`
- *free* `a` byte data structure: `SP -= a`

Segments — Heap (Dynamic Memory Allocation)

- some data "randomly" allocated/freed
- two-tier memory allocation:
  1. allocate large memory chunk (**heap segment**) from OS
     - base address + **break pointer** (BRK)
     - process can get more/give back memory from/to OS
  2. dynamically partition chunk into smaller allocations
     - `malloc`/`free` can be used in random oder
     - purely user-space, no need to contact kernel



> **Summary**
>
> **Processes**: recipe vs. cooking = program vs. process
> - processes = resource container for OS
> - process feels alone (has own CPU and memory)
> - OS implements multiprogramming through rapid process switching

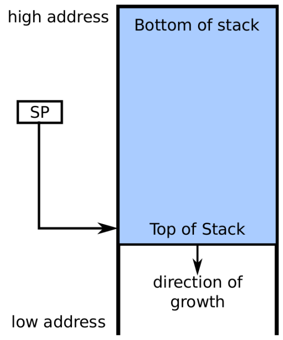
Process API

Execution Model — Assembler (simplified)

- **Principle**: OS interacts directly with compiled programs
  - switch between processes/threads ⇝ *save/restore* state
  - deal with/pass on *signals/exceptions*
  - receive *requests* from applications
- **Instructions**:
  - `mov`: Copy referenced data from second operand to first operand
  - `add`/`sub`/`mul`/`div`: Add,... from second operand to first operand
  - `inc`/`dec`: increment/decrement register/memory location
  - `shl`/`shr`: shift first operand left/right by amount given by second operand
  - `and`/`or`/`xor`: calculate bitwise and,... of two operands storing result in first
  - `not`: bitwise negate operand

Execution Model — Stack (x86)

- **stack pointer** (SP): holds address of stack top (growing downwards)
- **stack frames**: larger stack chunks
- **base pointer** (BP): used to organize stack frames



Execution Model — jump/branch/call commands (x86)

- `jmp`: continue execution at operand address
- `j$condition`: jump depending on PSW content
  - *true* ⇝ jump
  - *false* ⇝ continue
  - examples: `je` (jump equal), `jz` (jump zero)
- `call`: push function to stack and jump to it
- `return`: return from function (jump to return address)

Execution Model — Application Binary Interface (ABI)

- **Idea**: standardizes binary interface between programs, modules, OS:
  - executable/object file layout
  - calling conventions
  - alignment rules
- **calling conventions**: standardize exact way function calls are implemented
  ⇝ interoperability between compilers

Execution Model — calling conventions (x86)

- function call — **caller**:
  1. save local scope state
  2. set up parameters where function can find them
  3. transfer control flow
- function call — **called function**:
  1. set up new local scope (local variables)
  2. perform duty
  3. put return value where caller can find it
  4. jump back to caller (IP)

Passing parameters to the system

- parameters are passed through **system calls**
- call number + specific parameters must be passed
- parameters can be transferred through
  - **CPU registers** (~6)
  - **Main Memory** (heap/stack – more parameters, data types)
- ABI specifies how to pass parameters
- **return code** needs to be returned to application
  - *negative*: error code
  - *positive + 0*: success
  - usually returned via A+D registers

System call handler

- implements the actual service called through a syscall:
  1. saves tainted registers
  2. reads passed parameters
  3. sanitizes/checks parameters
  4. checks if caller has enough permissions to perform the requested action
  5. performs requested action in behalf of the caller
  6. returns to caller with success/error code

Process API — creation

- process creation events:
  1. system initialization
  2. process creation syscall
  3. user requests process creation
  4. batch job-initiation
- events map to two mechanisms:
  1. Kernel spawns initial user space process on boot (Linux: `init`)
  2. User space processes can spawn other processes (within their quota)

Process API — creation (POSIX)

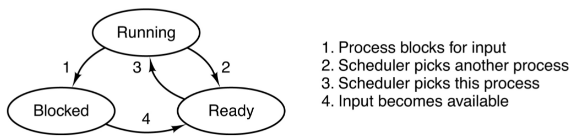
- `PID`: identifies process
- `pid = fork()`: duplicates current process:
  - returns 0 to new child
  - returns new `PID` to parent
  - ⇝ child and parent independent after `fork`
- `exec(name)`: replaces own memory based on executable file
  - `name` specifies binary executable file
- `exit(status)`: terminates process, returns `status`
- `pid = waitpid(pid, &status)`: wait for child termination
  - `pid`: process to wait for
  - `status`: points to data structure that returns information about the process (e.g., exit status)
  - passed `pid` is returned on success, `-1` otherwise
- **process tree**: processes create child processes, which create child processes, …
  - parent and child execute concurrently
  - parent waits for child to terminate (collecting the exit state)

Daemons

= program designed to run in the background
- detached from parent process after creation, reattached to process tree root (`init`)

Process States

- **blocking**: process does nothing but wait
  - usually happens on syscalls (OS doesn't run process until event happens)



Process Termination

- different termination events:
  1. normal exit (voluntary)
     - `return 0` at end of `main`
     - `exit(0)`
  2. error exit (voluntary)
     - `return x` ($x \neq 0$) at end of `main`
     - `exit(x)` ($x \neq 0$)
     - `abort()`
  3. fatal error (involuntary)
     - OS kills process after exception
     - process exceeds allowed resources
  4. killed by another process (involuntary)
     - another process sends kill signal (only as parent process or administrator)

Exit Status

- voluntary exit: process returns exit status (integer)
- resources not completely freed after process terminates ⇝ **Zombie** or **process stub** (contains exit status until collected via `waitpid`)
- **Orphans**: Processes without parents
  - usually adopted by `init`
  - some systems kill all children when parent is killed
- exit status on involuntary exit:
  - Bits `0-6`: signal number that killed process (`0` on normal exit)
  - Bit `7`: set if process was killed by signal
  - Bits `8-15`: `0` if killed by signal (exit status on normal exit)

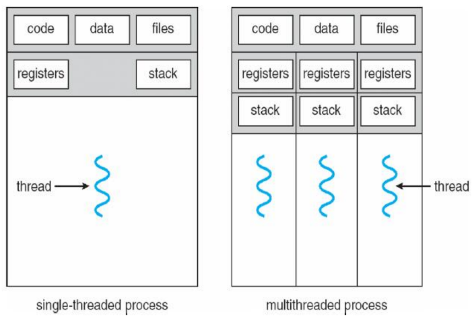
Threads

Processes vs. Threads

- **Traditional OS**: each process has
  - own address space
  - own set of allocated resources
  - *one* thread of execution (= one execution state)
- **Modern OS**: processes + threads of execution handled more flexibly
  - *processes* provide abstraction of address space and resources
  - *threads* provide abstraction of execution states of that address space
- **Exceptions**:
  - sometimes different threads have different address spaces
  - *Linux*: threads = regular processes with shared resources and AS regions

Threads — why?

- many programs do multiple things at once (e.g. web server)
  - ⇝ writing program as many sequential threads may be easier than with blocking operations
- **Processes**: rarely share data (if, then explicitly)
- **Threads**: closely related, share data



Threads — POSIX

- `PThread`: base object with
  - *identifier* (thread ID, TID)
  - *register set* (including IP and SP)
  - *stack area* to hold execution state
- `Pthread_create`: create new thread
  - Pass: *pointer* to `pthread_t` (will hold TID after successful call)
  - Pass: *attributes, start function, arguments*
  - Returns: `0` on success, error value else
- `Pthread_exit`: terminate calling thread
  - Pass: exit code (casted to void pointer)
  - Free's resources (e.g. stack)
- `Pthread_join`: wait for specified thread to exit
  - Pass: `ptread_t` to wait for (or `-1` for any thread)
  - Pass: pointer to pointer for exit code
  - Returns: `0` on success, error value else
- `Pthread_yield`: release CPU to let another thread run

Threads — Problems

- **Processes vs. Threads**:
  - *Processes*: only share resources explicitly
  - *Threads*: more shared state → more can go wrong
- **Challenges**: programmer needs to take care of
  - *activities*: dividing, ordering, balancing
  - *data*: dividing
  - *shared data*: access synchronizing

PCB vs. TCP

- **PCB** (*process control block*): information needed to implement processes
  - always known to OS
- **TCB** (*thread control block*): per thread data
  - OS knowledge depends on *thread model*

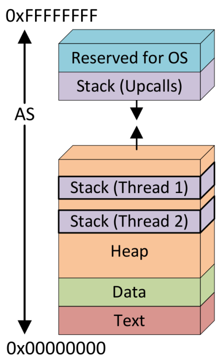
PCB	TCB
Address space	Instruction pointer
Global variables	Registers
Open files	Stack
Child processes	State
Pending alarms	

Thread models

- **Kernel Thread**: known to OS kernel
- **User Thread**: known to process
- **N:1-Model**: kernel only knows one of possibly multiple threads
  - N:1 user threads = *user level threads* (ULT)
- **1:1-Model**: each user thread maps to one kernel thread
  - 1:1 user threads = *kernel level threads* (KLT)
- **M:N-Model** (hybrid model): flexible mapping of user threads to less kernel threads

Thread models — N:1

- Kernel only manages process → multiple threads unknown to kernel
- Threads managed in user-space library (e.g. GNU Portable Threads)
- **Pro**:
  + faster thread management operations (up to 100 times)
  + flexible scheduling policy
  + few system resources
  + usable even if OS doesn't support threads
- **Con**:
  - no parallel execution
  - whole process blocks if one user thread blocks
  - reimplementing OS parts (e.g. scheduler)
- **Stack**:
  - main stack known to OS used by thread library
  - own execution state (= stack) dynamically allocated by user thread library for each thread
  - possibly own stack for each exception handler
- **Heap**:
  - concurrent heap use possible
  - *Attention*: not all heaps are reentrant
- **Data**: divided into BSS, data and read-only data here as well

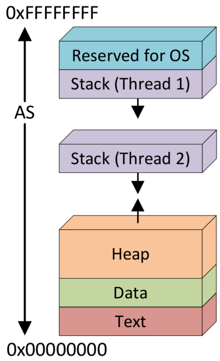


Thread models — 1:1

- kernel knows + manages every thread
- **Pros**:
  + real parallelism possible
  + threads block individually
- **Cons**:
  - OS manages every thread in system (TCB, stacks,...)
  - Syscalls needed for thread management
  - scheduling fixed in OS
- **Stack**:
  - own execution state (= stack) for every thread
  - possibly own stack for (each) exception handler
- **Heap**:
  - parallel heap use possible
  - *Attention*: not all heaps are thread-safe
  - if thread-safe: not all heap implementations perform well with many threads
- **Data**: divided into BSS, data and read-only data here as well

Thread models — M:N

- **Principle**: M ULTs are maps to (at most) N KLT
  - *Goal*: pros of ULT and KLT — non-blocking with quick management
  - create sufficient number of KLTs and flexibly allocate ULTs to them



  - *Idea*: if ULT blocks ULTs can be switched in userspace
- **Pros**:
  + flexible scheduling policy
  + efficient execution
- **Cons**:
  - hard to debug
  - hard to implement (e.g. blocking, number of KLTs,...)
- **Implementation — Up-calls**:
  - kernel notices that thread will block → sends signal to process
  - up-call notifies process of thread id and event that happened
  - exception handler of process schedules a different process thread
  - kernel later informs process that blocking event finished via other up-call

Summary

- programs often do closely related things at once
  - mapped to thread abstraction: multiple threads of execution operate in same process
- differentiation between process information (PCB) and thread information (TCB)
- **thread models**:
  - $N : 1$: threads fully managed in user-space
  - $1 : 1$: threads fully managed by kernel
  - $M : N$: threads are flexibly managed either in user-space or kernel
- multi-threaded programs operate on same data concurrently or even parallel:
  - *synchronization*: accessing such data must be synchronized
  - → makes writing such programs challenging

Scheduling

Motivation

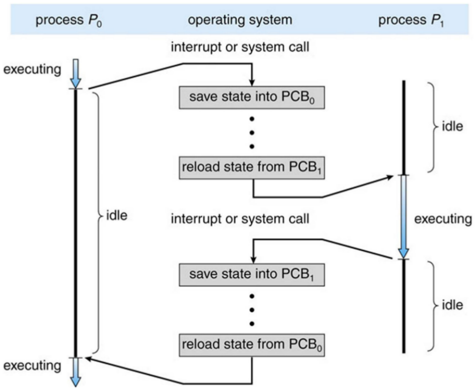
- K jobs ready to run, $K > N \geq 1$ CPUs available
- **Scheduling Problem**:
  - Which jobs should kernel assign to which CPUs?
  - When should it make decision?

Dispatcher

- **Dispatcher**: performs actual process switch
  - mechanism
  - save/restore process context
  - switch to user mode
- **Scheduler**: selects next process to run based on *policy*

Voluntary Yielding vs. Preemption

- kernel responsible for CPU switch
- kernel doesn't always run → can only dispatch different process when invoked
- **cooperative multitasking**: running process performs *yield* syscall
  → kernel switches process
- **preemptive scheduling**:
  - kernel invoked in certain time intervals
  - kernel makes scheduling decisions after every time-slice



Scheduling — Process States

- **new**: process was created but did not run yet
- **running**: instructions are currently being executed
- **waiting**: process is waiting for some event
- **ready**: process is waiting to by assigned a processor
- **terminated**: process has finished execution

Scheduling — long-term vs. short-term

- **Short-term scheduler** (CPU Scheduler, focused on in this lecture):
  - selects process to run next, allocates CPU
  - invoked frequently (ms) ⇝ must be fast
- **Long-term scheduler** (job scheduler):
  - selects process to be brought into ready queue
  - invoked very infrequently (s, m) ⇝ can be slow
  - controls degree of *multiprogramming*

Scheduling queues

- **job queue**: set of all processes in system
- **ready queue**: process in main memory, ready or waiting
- **device queue**: processes waiting for I/O device

Scheduling Policies — Categories

- **batch scheduling**:
  - still widespread in business (payroll, inventory,…)
  - no users waiting for quick response
  - non-preemptive algorithms acceptable → less switches → less overhead
- **interactive scheduling**:
  - need to optimize for response time
  - preemption essential to keep processes from hogging CPU
- **real-time scheduling**:
  - guarantee job completion within time constraints
  - need to be able to plan when which process runs + how long
  - preemption not always needed

Scheduling Policies — Goals

- **General**:
  - *fairness*: give each process fair share of CPU
  - *balance*: keep all parts of system busy
- **batch scheduling**:
  - *throughput*: number of processes that complete per time unit
  - *turnaround time*: time from job submission to job completion
  - *CPU utilization*: keep CPU as busy as possible
- **interactive scheduling**:
  - *waiting time*: reduce time a process waits in waiting queue
  - *response time*: time from request to first response
- **real-time scheduling**:
  - *meeting deadlines*: finishing jobs in time
  - *predictability*: minimize jitter

Scheduling Policies — first come first served

- intuitively clear
- **Example**: 3 processes arrive at time 0 in the order P_1, P_2, P_3

Process	Burst time	Turnaround time
P_1	24	24
P_2	3	27
P_3	3	30

- ⇝ average turnaround time 27 → *can we do better?*
- **Conclusion**: if processes would arrive in order P_2, P_3, P_1, average turnaround time would be 13
  ⇝ *good scheduling can reduce turnaround time*

Scheduling Policies — shortest job first

- **Benefits**: optimal average turnaround/waiting/response time
- **Challenge**: cannot know job lengths in advance
- **Solution**: predict length of next CPU burst for each process
  ⇝ schedule process with shortest burst next
- **Burst Estimation**: *exponential averaging*
  - $\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$
  (t_n: actual length of n-th CPU burst, τ_{n+1}: predicted length of next CPU burst, $0 \leq \alpha \leq 1$)

Process Behavior — CPU bursts

- CPU bursts exists because processes wait for I/O
- **CPU-bound processes**: spends more time doing computations
  ⇝ few very long CPU bursts
- **I/O-bound processes**: spends more time doing I/O
  ⇝ many short CPU bursts

Scheduling Policies — preemptive shortest-job-first

- SJF optimizes waiting/response time
  ⇝ what about throughput?
- **Problem**: CPU-bound jobs hold CPU until exit or I/O → *poor I/O utilization*
- **Idea**: SJF, but preempt periodically to make new scheduling decision
  - each time slice: schedule job with shortest remaining time next
  - alternatively: schedule job with shortest next CPU burst

Scheduling Policies — round robin

- **Problem**: batch schedulers suffer from starvation and don't provide fairness
- **Idea**: each process runs for small CPU time unit
  - *time quantum/time slice* length: usually 10-100ms
  - preempt processes that have not blocked by end of time slice
  - append current thread to end of run queue, run next thread
- **Caution**: time slice length needs to balance interactivity and overhead!
  → if time slice length in the area of dispatch time, 50% of CPU time wasted for process switching

Scheduling Policies — virtual round robin

- **Problem**: RR is unfair for I/O-bound jobs: they block before using up time quantum
- **Idea**: put jobs that didn't use up their quantum in additional queue
  - store share of unused time-slice
  - give those jobs additional queue priority
  - put them back into normal queue afterwards

Scheduling Policies — (strict) priority scheduling

- **Problem**: not all jobs are equally important
  ⇝ different priorities (e.g., 4)
- **Solution**: associate priority number with each process
  - RR for each priority
  - *aging*: old low priority processes get executed before new higher priority processes

Scheduling Policies — multi-level feedback queue

- **Problem**: context switching expensive
  ⇝ trade-off between interactivity and overhead?
- **Goals**:
  - higher priority for I/O jobs (usually don't use up quantum)
  - low priority for CPU jobs (rather run them longer)
- **Idea**: different queues with different priorities and time slice lengths
  - schedule queues with (static) priority scheduling
  - double time slice length in each next-lower priority
  - process to higher priority when they don't use up quantum repetitively
  - process to lower priority when they use up quantum repetitively

Scheduling Principles — priority donation

- **Problem**: Process B (higher priority) waits for process A (lower priority)
  ⇝ B has now effectively lower priority
- **Solution**: *priority donation*
  - give A priority of B as long as B waits for A
  - if C, D, E wait for B → A gets highest priority of B, C, D, E

Scheduling Policies — lottery scheduling

- issue number of lottery tickets to processes (amount depending on priority)
- amount of tickets controls average proportion of CPU for each process
- **Scheduling**: scheduler draws random number N, process with N-th ticket is executed
- processes can transfer tickets to other processes if they wait for them

Summary

- **phases**: processes have phases of communication and waiting for I/O
  → appropriate switching between processes increases computing system utilization
- **goal-based**: scheduler decides what appropriate means based on goals
  - *long-term scheduler*: degree of multiprogramming
  - *short-term scheduler*: which process to run next
- **dispatching**: only happens when OS is invoked
  - *cooperative scheduling*: currently running thread yields (syscall)
  - *preemptive scheduling*: OS is called periodically to switch threads

Inter Process Communication

Overview

- **Reasons** for cooperating processes:
  - *information sharing*: share file/data-structure in memory
  - *computation speed-up*: break large tasks in subtasks ⇝ parallel execution
  - *modularity*: divide system into collaborating modules with clean interfaces
- **IPC**: allows data exchange
  - *message passing*: explicitly send/receive information using syscalls
  - *shared memory*: physical memory region used by multiple processes/threads

IPC — message passing

- = mechanism for processes to communicate and synchronize
- message passing facilities generally provide `send` and `receive`
- **Implementations**:
  - hardware bus
  - shared memory
  - kernel memory
  - network interface card (NIC)
- **Direct messages**: processes explicitly named when exchanging messages
- **Indirect messages**: sending to/receiving from *mailboxes*
  - first communicating process creates mailbox, last destroys
  - processes can only communicate through shared mailbox

Indirect messages – synchronization

- **Blocking** (synchronous):
  - *blocking send*: sender blocks until message is received
  - *blocking receive*: receiver blocks until message is available
- **Non-blocking** (asynchronous):
  - *non-blocking send*: sender sends message, then continues
  - *non-blocking receive*: receiver receives valid message or `null`

Messaging — Buffering

- messages are *queued* using different capacities while being in-flight
- **zero capacity**: no queuing
  - *rendezvous*: sender must wait for receiver
  - message is transferred as soon as receiver becomes available → no latency/jitter
- **bounded capacity**: finite number + length of messages
  - sender can send before receiver waits for messages
  - sender must wait if link is full
- **unbounded capacity**:
  - sender never waits
  - memory may overflow → potentially large latency/jitter between `send` and `receive`

Messaging — POSIX message queues

- **create** or open existing message queue:
  `mqd_t mq_open (const char *name, int oflag);`
  - `name` ist path in file system
  - access permission controlled through file system access permission
- **send** message to message queue:
  `int mq_send (mqd_t md, const char *msg, size_t len, unsigned priority);`
- **receive** message with highest priority in message queue:
  `int mq_receive (mqd_t md, char *msg, size_t len, unsigned * priority);`
- **register** callback handler on message queue (to avoid polling):
  `int mq_notify (mqd_t md, const struct sigevent *sevp);`
- **remove** message queue:
  `int mq_unlink (const char *name);`

Shared Memory

- **Principle**: communicate through region of shared memory
  - every write to shared region is visible to all other processes
  - hardware guarantees that always most recent write is read
- **Implementation**: message passing via shared memory is application-specific
- **Problems**: using shared memory in a safe way is tricky
  - *cache coherency protocol*: makes usage with many processes/CPUs hard
  - *race conditions*: makes usage with multiple writers hard

Shared Memory — POSIX shared memory

- **create** or open existing POSIX shared memory object:
  `int shm_open (const char *name, int oflag, mod_t mode);`
- **set** size of shared memory region:
  `ftruncate (smd, size_t len);`
- **map** shared memory object to address space:
  `void* mmap (void* addr, size_t len, [...], smd, [...]);`
- **unmap** shared memory object from address space:
  `int munmap (void* addr, size_t len);`
- **destroy** shared memory object:
  `int shm_unlink (const char *name);`

Shared Memory — sequential memory consistency

= *the result of execution as if all operations were executed in some sequential order, and the operations of each processor occurred in the order specified by the program.*

- **Model**:
  - all memory operations occur one at a time in *program order*
  - ensures write atomicity
- **Reality**: compiler and CPU re-order instructions to *execution order*
  → without SC many processes on many CPU behave worse than preemptive threads on 1 CPU

Shared Memory — memory consistency model

- **Problem**:
  - CPUs generally not sequentially consistent
  - compilers do not generate code in program order

Synchronization — race conditions

- **Assume**: sequential memory consistency → no atomic memory transactions!
- **Critical Sections**: protect instructions inside critical section from concurrent execution

Critical Sections — desired properties

- **mutual exclusion**: at most one thread can be in the CS at any time
- **progress**: no thread running outside of CS may block other thread from getting in
- **bounded waiting**: once a thread starts trying to enter CS, there is a bound on number of times other threads get in

Critical Sections — disabling interrupts

- kernel only switches on interrupts (usually on *timer interrupt*)
  → have per-thread *do not interrupt* (DNI)-bit
- **single-core system**:

- enter CS: set DNI bit
- leave CS: clear DNI bit
- **Advantages**:
  + easy + convenient in kernel
- **Disadvantages**:
  - *only works on single-core systems*: disabling interrupts on one CPU doesn't affect other CPUs
  - *only feasible in kernel*: don't want to give user power to turn off interrupts!

Critical Sections — lock variables

- define global `lock` variable
  - only enter CS if `lock` is 0, set to 1 on enter
  - wait for lock to become 0 otherwise (*busy waiting*)
- **Problem**: doesn't solve CS problem! Reading/Setting lock not atomic!

Critical Sections — spinlocks

- to make lock variable approach work, lock variable must be tested and set at same time atomically:
- **x86**: `xchg` can atomically exchange memory content with register
  - exchanges register content with memory content
  - returns previous memory content of lock
  - ⇝ implementation of critical section as *spinlock*:

```
void enter_critical_section (volatile bool *lock) {
  while (xchg(lock, 1) == 1); // lock = 1, return old value
                               // repeat until old value != 1
}

void leave_critical_section (volatile bool *lock) {
  *lock = 0;
}
```

- **Advantages**:
  + *mutual exclusion*: only one thread can enter CS
  + *progress*: only thread within CS hinders others of getting in
- **Disadvantages**:
  - *bounded waiting*: no upper bound

Spinlocks — Limitations

- **Congestion**:
  - if most times there is no thread in CS when another tries to enter, then spinlocks are very easy + efficient
  - if CS is large or many threads try to enter, spinlocks might not be good choice as all threads actively wait spinning
- **Multicore**: memory address is written at every atomic swap operation
  → memory is expensively kept coherent
- **Static Priorities** (e.g., *priority inversion*): if low-priority threads hold lock it will never be able to release it, because it will never be scheduled

Spinlocks — sleep while wait

- **Problem**: busy part of busy waiting
  - wastes resources,
  - stresses cache coherence protocol,
  - can cause priority inversion problem
- **Idea**:
  - threads sleep on locks if occupied
  - wake up threads one at a time when lock becomes free

Spinlocks — semaphore

- two new syscalls operating on `int` variables:
  - `wait (&s)`: if `s > 0`: `s--` and continue, otherwise let caller sleep
  - `signal (&s)`: if no thread is waiting: `s++`, otherwise wake one up
- initialize `s` to maximum number of threads that may enter CS
  - `wait` = `enter_critical_section()`
  - `signal` = `leave_critical_section()`
- **mutex** (semaphore): semaphore initialized to 1 (only admits one thread at a time into CS)
- **counting semaphore**: semaphore allowing more than one thread into CS at a time

Semaphore — implementation

- `wait` and `signal` calls need to be carefully synchronized (otherwise *race condition* between checking and decrementing `s`)
- **signal loss** can occur when waiting and waking threads up at same time
  ⇝ each semaphore has **wake-up queue**:
  - *weak semaphores*: wake up random waiting thread on `signal`
  - *strong semaphores*: wake up thread strictly in order which they started `wait`ing
- **Advantages**:
  + *mutual exclusion*: only one thread can enter CS for mutexes
  + *progress*: only thread within CS hinders others to get in
  + *bounded waiting*: strong semaphores guarantee bounded waiting
- **Disadvantages**:
  - every enter and exit of CS is syscall → slow

Fast User Space mutex

- **spinlock**:
  + quick when wait-time is short
  - waste resources when wait-time is long
- **semaphore**:
  + efficient when wait-time is long
  - syscall overhead at every operation
- **futex**:
  - userspace + kernel component
  - try to get into CS with userspace spinlock
    – CS busy → use syscall to put thread to sleep
    – otherwise → enter CS with now locked spinlock completely in userspace

Summary

- **communication** between processes/threads often needed
  - *message passing*: provide explicit send/receive functions to exchange messages
  - *implicitly/explicitly shared memory* between threads/processes: allows information exchange
- **data races**: need to be taken into account when communicating
- **synchronization techniques**:
  - interlocked atomic operations
  - spinlocks
  - semaphores
  - futexes

Synchronization and Deadlocks

Producer-Consumer Problem

- **Definition**:
  - buffer is shared between producer and consumer (LIFO)
  - `count` integer keeps track of number of currently available items
  - producer produces item → placed in buffer, `count++`
  - buffer full → producer needs to sleep until consumer consumed an item
  - consumer consumes item → remove item from buffer, `count--`
  - buffer empty → consumer needs to sleep until producer produces item
- **Problem**: *race condition* on `count`

Producer-Consumer Problem — condition variables

- **Solution**: can be solved with mutex + 2 counting semaphores
  - hard to understand
  - hard to get right
  - hard to transfer to other problems
- **condition variables**: allow blocking until condition is met
  - usually suitable for same problems but much easier to get right
- **Idea**:
  - new operation performs *unlock*, *sleep*, *lock* atomically
  - new wake-up operation is called with lock held
  → simple mutex lock/unlock around CS + no signal loss
- **Pthread** condition variables:
  - `pthread_cond_init`: create + initialize new CV
  - `pthread_cond_destroy`: destroy + free existing CV
  - `pthread_cond_wait`: block waiting for signal
  - `pthread_cond_timedwait`: block waiting for signal or timer
  - `pthread_cond_signal` : signal another thread to wake up
  - `pthread_cond_broadcast`: signal all threads to wake up

Reader-Writer Problem

- **Problem**: model access to shared data structures

```c
void producer()
{
  Item newItem;

  for(;;) // ever
  {
    newItem = produce();

    mutex_lock( &lock );
    while( count == MAX_ITEMS )
      cond_wait( &less, &lock );

    insert( newItem );
    count++;

    cond_signal( &more );
    mutex_unlock( &lock );
  }
}
```

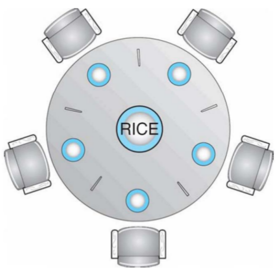
```c
void consumer()
{
  Item item;

  for(;;) // ever
  {
    mutex_lock( &lock );
    while( count == 0 )
      cond_wait( &more, &lock );

    item = remove();
    count--;

    cond_signal( &less );
    mutex_unlock( &lock );

    consume( item );
  }
}
```

- many threads compete to read/write same data
- *readers*: only read data set, not performing any updates
- *writers*: both read and write
- ⇝ using single mutex for read/write operations is not a good solution! (unnecessarily blocking out multiple readers while no writer is present)

- **Idea**: locking should reflect different semantics for reading/writing
  - no writing thread → multiple readers may be present
  - writing thread → no other reader/writer allowed

Dining-Philosophers Problem

- **Definition**: 5 philosophers with cyclic workflow:
  1. think
  2. get hungry
  3. grab one chopstick
  4. grab other chopstick
  5. put down chopsticks
- **Rules**:
  - no communication
  - no atomic grabbing of both chopsticks
  - no wrestling
- **Abstraction**: models threads competing for limited number of resources **Problem**: what happens if all philosophers grab left chopstick at once?
- **Deadlock workarounds**:
  - *deadlock avoidance*: just 4 philosophers allowed at table of 5
  - *deadlock prevention*: odd philosophers take left chopstick first, even ones take right first → *deadlock prevention*



Deadlocks

- **Deadlocks** can arise if all four conditions hold simultaneously:
  - *mutual exclusion*: limited resource access (can only be shared with finite number of users)
  - *hold and wait*: wait for next resource while already holding at least one
  - *no preemption*: granted resource cannot be taken away but only handled back voluntarily
  - *circular wait*: possibility of circularity in requests graph

Deadlocks — countermeasures

- **prevention**: pro-active, make deadlocks impossible to occur
- **avoidance**: decide on allowed actions based on a-priori knowledge
- **detection** (*recovery*): react after deadlock happened

Deadlocks — prevention

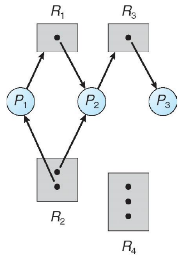
- **Goal**: negate at least one of the required deadlock conditions:
  - *mutual exclusion*: buy more resources, split into pieces, virtualize
  - *hold and wait*: get all resources en-bloque, 2-phase-locking
  - *no preemption*: virtualize to make preemptable
  - *circular wait*: reorder resources, prevent through partial order on resources

Deadlocks — avoidance

- **safe state**: system is in safe state → no deadlocks
- **unsafe state**: system is in unsafe state → deadlocks possible
- **avoidance**: on every resource request decide if system stays in safe state
  → *resource allocation graph*

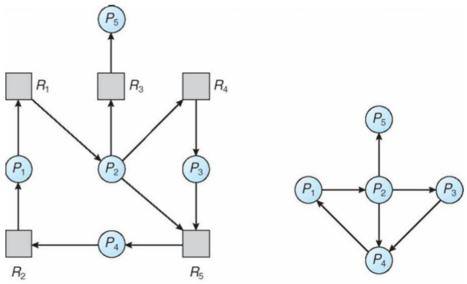
Deadlock Avoidance — resource allocation graph

- **principle**: view system state as graph
  - *processes* = round nodes
  - *resources* = square nodes
  - *resource instance* = dot in resource node
  - *resource requests/assignments* = edges
    - resource → process = resource is assigned to process
    - process → resource = process is requesting resource



Deadlocks — detection

- **Principle**: allow system to enter deadlock → detection → recovery scheme
- **wait-for graph** (WFG):
  - *processes* = nodes
  - *wait-for relationship* = edges
- periodically invoke algorithm searching for cycle in graph
  ⇝ cycle exists → deadlock exists



Deadlocks — recovery

- **Process termination**:
  - *all*: abort all deadlocked processes
  - *selective*: abort one process at a time until deadlock is eliminated
- **Termination order**: in which order should processes be aborted?
  - process priority
  - how long already computed? how much longer for completion?
  - amount of resources used
  - amount of resources needed for completion
  - how many processes will need to be terminated
  - interactive or batch?
- **Resource preemption**:
  - *victim selection*: minimize cost
  - *rollback*: perform periodic snapshots, abort process to preempt resources → restart from last safe state
  - *starvation*: same process may always be picked as victim ⇝ include rollback count in cost factor

Summary

- **classical synchronization problems**: model synchronization problems occurring in reality
  - *producer-consumer*: shared use of buffers/queues
  - *reader-writer*: shared access to data structures
  - *dining philosophers*: competition for limited resources
- such synchronization problems occur very often when programming operating systems
- **parallelism**: introduced by multiple processors + multiprogramming, needs to be considered carefully when writing OS